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THE USE OF VIRTUAL FIXTURES AS PERCEPTUAL OVERLAYS TO ENHANCE OPERATOR PERFORMANCE IN REMOTE ENVIRONMENTS

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FOR THE COMMANDER

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This report introduces the notion of virtual fixtures for use in telepresence systems. Tools and fixtures in the real world (e.g., a ruler guiding a pencil) enhance human performance by guiding manual operations, providing localizing references, reducing mental workload, and increasing precision. Virtual fixtures are computer-generated percepts overlaid on top of the reflection of a remote workspace which can provide similar benefits. Because such perceptual overlays are virtual constructions they can be diverse in modality, abstract in form, and custom tailored to individual situations. This study investigates the potential of virtual fixtures by implementing simple combinations of haptic surfaces and auditory sensations as virtual perceptual aids in a standardized telemanipulation task. Subjects viewed the remote environment through a vision system while wearing an upper-body exoskeleton. Eight subjects controlled a slave robot arm to perform standard Fitts' law peg-insertion tasks with and without the aid of a variety of virtual fixtures. Fixtures composed of haptic and auditory perceptual overlays increased operator performance up to 70%. Simple fixtures devised from basic elements can be powerful perceptual aids; a workstation environment might be developed to allow a teleoperator to design and implement virtual fixtures interactively.

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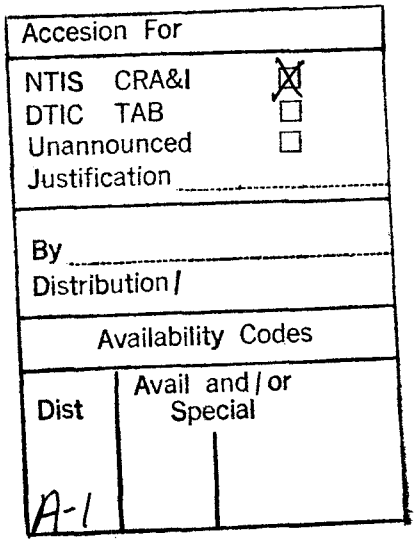
PREFACE

This work was performed with facilities and support from the Armstrong Laboratory with headquarters at Brooks Air Force Base, Texas, and its Crew Systems Directorate, Human Sensory Feedback Group, at Wright-Patterson AFB, Ohio. Support for this work was provided in part through the Air Force Office of Scientific Research Laboratory Graduate Fellowship Program (LGFP). The work is part of a graduate thesis done in conjunction with the Center for Design Research, Stanford University, Stanford, California.



Footnote: the Virtual Fixtures project was funded by the Air Force Office of Scientific Research (AFOSR) and is therefore entered into the public domain. The research was conducted at Stanford, Air Force Research Laboratory (Armstrong Lab), and NASA Ames Research Center. The objective of the Virtual Fixtures platform was to research whether it was possible to incorporate interactive virtual objects (called "virtual fixtures") into a user's perception of real workspaces. This concept later became commonly referred to as augmented reality (AR) or mixed reality (MR).

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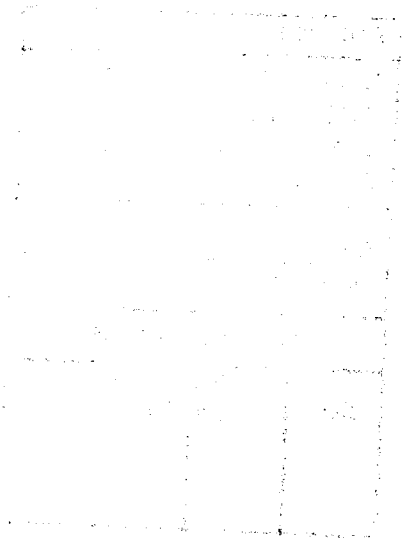

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INTRODUCTION

Telepresence and the Transparent Interface

The fundamental purpose of a telepresence system is to extend an operator's sensory-motor facilities and problem solving abilities to a remote environment [15]. Telepresence is achieved by projecting the operator's manipulatory dexterity to a remote environment while reflecting sensory feedback so realistically that the operator feels present in the remote site [1]. To enhance operator performance and understanding within remote environments, most research and development of telepresence systems has been directed towards increasing the *transparency* of the link between operator and environment. Much of this work has focused upon improving the fidelity and presentation of the reflected sensory information. Other work has focused upon making the *projection* of the operator's kinematics and dynamics more naturally mapped into the remote environment [4, 5, 6, 9, 10]. The culmination of such research efforts could be a transparent link between human and machine; a user interface through which information is passed so naturally between operator and environment that the user achieves a complete sense of presence within the remote site.

Although unattainable by current technology, the linking of an operator to a remote environment through a perfectly transparent interface should yield a human-machine system that allows an operator to perform just *as well* in the remote environment as in a real environment. Although the achievement of such an interface would be an important milestone in human-machine systems, the motivation for the work described in this paper is somewhat different. Rather than looking for methods of enhancing the transparency of the interface, this work is actually focused upon corrupting the transparency of the interface by introducing abstract perceptual information between human and machine. It is believed that abstract percepts overlaid on top of the reflection of the workspace can be implemented as perceptual tools that enhance an operator's performance and understanding. It is not suggested that such an approach is a replacement for a high fidelity link between operator and environment, but rather a supplement. The culmination of work along these lines could be a telepresence system which does more than simply *project* an operator's

abilities into a workspace, but actually *enhances and expands* the operator's abilities within that workspace beyond natural capabilities.

The Concept of Perceptual Overlays

When asked to draw a straight line in the real world, human performance can be greatly enhanced by using a simple tool such as a ruler. The use of a ruler reduces the amount of mental processing required to perform the task, speeds an operator's line drawing ability, and most of all allows an operator to draw a significantly better line than if no ruler had been used at all. Without a ruler, line drawing is a manual task that requires constant visual supervision and hand/eye coordination. With a ruler, line drawing is not only faster and straighter, but the dependance on visual feedback is reduced, freeing up that modality for other uses. What is more, a ruler is often used as a barrier to protect against dangerous or destructive failures, protecting the work-piece from the slip of a pencil or knife. Such guidance and protection allows the operator to ease mental criteria for task success and failure, reducing the level of concentration devoted to the task. Although a simple tool by any standard, a common ruler is clearly a powerful performance aid in manual line drawing tasks.

Although the use of a ruler to assist in straight-line drawing is an effective means of enhancing human performance, can such a process be generalized beyond line drawing? Ruler-use can be thought of as nothing more than a process of *overlaying* abstract sensory information on top of a workspace. Thus, a ruler can be generalized as a particular "perceptual overlay" designed to enhance line drawing performance. In the case of a ruler, the overlaid sensory information represents a rigid surface that is perceived haptically and visually by the user. By overlaying this generic piece of sensory information on top of the workspace, the user has reduced the mental and physical demands of the straight line drawing task and performance is greatly enhanced.

If a simple ruler-like perceptual overlay can so greatly enhance the performance of real world manipulatory tasks like straight line drawing, it seems that computer generated perceptual overlays could be developed within

virtual environments to enhance the performance of tele-manipulation tasks within remote worksites. Just as a ruler can be overlaid on top of a real workspace, such virtual perceptual overlays could be overlaid on top of the sensory feedback from a remote workspace.

The Virtual Fixture Metaphor

Because the abstract notion of overlaid sensory information is as difficult to conceptualize as it is to talk about, I will introduce a *virtual fixture metaphor* as a means of describing such computer generated sensations as concrete physical structures. It must be stressed that the point of this metaphor is intended to facilitate the understanding of, and interaction with perceptual overlays and should not be taken so literally as to limit the scope of the perceptual overlay concept. *Virtual fixtures* are thus defined as abstract sensory information overlaid on top of reflected sensory feedback from a remote environment. Although overlaid on top of the user's perception of the remote environment, virtual fixtures are completely independent of all information from the remote site and are thus immune from communication delays and bandwidth limitations.

Like the ruler guiding the pencil, virtual fixtures overlaid on top of a remote workspace could act to reduce mental processing required to perform the task, reduce the work load of certain sensory modalities, and most of all allow precision and performance to exceed natural human abilities. Although virtual fixtures could be functionally equivalent to fixtures in the real world, there are many advantages inherent to virtual fixtures because they are computer simulations rather than real physical hardware. When overlaid on a workspace, the fixtures only interact with the user and not with the workspace itself. Thus fixtures can occupy the same physical space as objects in the workspace. This means that the workspace geometry imposes no constraints upon the placement or configuration of virtual fixtures. What is more, such fixturing has no mass, has no physical or mechanical constraints, requires no machining time or maintenance, can be easily prototyped and modified, and can essentially be transported to remote locations using nothing more than standard communication links.

If we explore the concept of virtual fixtures using the simple ruler example as the starting point, the first elements to consider might be rigid planar surfaces. Such fixtures would be composed of haptic sensations generated by reflecting simulated forces to the operator through a force-reflecting master. As the operator interacts with the modeled surfaces, the reaction forces would be computed and reflected appropriately. Of course, such fixtures are by no means limited to rigid surfaces. Abstracting the fixturing concept, we might consider modeling compliant surfaces, damped surfaces, even viscous or coulomb frictional contacts. In fact, the simulation environment offers such freedom that fixtures could even be developed as attractive or repulsive fields. Although fixtures composed of haptic sensations offer endless possibilities, the fixturing concept is not limited to that modality. Abstract fixtures could be composed of visual, auditory, even tactile sensations used alone or in cross-modal combinations. For example, if a haptic fixture composed of rigid planar surfaces or attractive force fields was developed to aid a particular task, an audio, visual, or vibratory signal could be mapped to various locations along the fixture to enhance interaction. Such additional modalities could be used to indicate deviations from a trajectory, proximity to a danger zone, even provide feedback of velocities or accelerations.

Abstracting the fixturing concept further, we could imagine virtual fixtures imbued with particular visual qualities to enhance interaction with environments. For example, virtual fixtures composed of haptic surfaces could be modeled with optical properties to suit the task at hand. The fixture might be invisible to the user if the operator gains no benefit from visual cues, it could be made to look like a solid object if rich visual cues are useful for the task, it could even be made to look like a transparent glassy solid if visual cues are important but the user wants to avoid obscuring the workspace. Fixtures might even be designed as visual filters to block particular distractions, enhance contrast, provide depth cues, even magnify a part of the workspace. One can even imagine the benefit of a fixture composed of compliant surfaces which changes color or brightness with compression. Previous work with targeting cues [3], predictive displays [2, 14, 20, 21, 22], and perspective overlays [11, 25] has demonstrated that overlaid visual cues can enhance performance and understanding within a teleoperation environment.

If the description of virtual fixtures thus far seems too abstract, a simple example may drive the concept home. Imagine a situation where a teleoperating surgeon performs a delicate procedure on a patient. Although such uses of telerobotics are still in the research phase, it is an application that demands a high degree of human performance within a remote workspace. Now imagine that a virtual fixture is being used by the doctor to enhance his abilities in this procedure. The fixture might appear to the doctor like a flat plane of glass with a grooved guide for the scalpel. The glass-like virtual fixture might actually pass directly through a patient's body, preventing the scalpel from penetrating below a particular depth but not obscuring vision of the tissue below. By sliding the scalpel along the edge of a groove in the fixture, the surgeon could make a perfect incision. The slightest deviation from the target trajectory might be reported by an audio or tactile signal. The power and flexibility of such a system would be unmatched by actual physical tooling. Besides the fact that such a fixture in the real world could not pass directly through a patient's body, it could not be put in place at the touch of a button, removed at the touch of another button, or easily altered as conditions change. What is more, virtual fixturing does not have to be fabricated, sterilized, monitored, or maintained.

Perceptual Workstation Environment

Although the notion of virtual fixturing does seem promising, if the development of fixtures requires complex computation or intimate knowledge of the workspace to be effective, robot autonomy might be a preferred solution to the task at hand. If, on the other hand, effective fixtures could be developed out of basic building blocks and quickly implemented by a teleoperator in an interactive environment, fixtures could be used in unstructured or changing environments unsuitable for autonomous systems. Thus, it is proposed that a workstation type environment be developed to allow teleoperators to design and implement assistive fixtures when confronted with an unknown task in an unstructured environment upon first encounter. With such a workstation in mind, the study described in this paper investigates the use of simple haptic surfaces and auditory fields as perceptual aids in a simple peg insertion task. Although a workstation environment could implement more sophisticated surfaces or fields including a more diverse array of sensory modalities, it was

thought that if simple combinations of forces and sounds could be made into effective fixtures, the potential of virtual fixtures would be adequately displayed.

Fitts' Law Performance Test

To quantify teleoperator performance in a remote manual task, a Fitts' Law paradigm was chosen because of its general acceptance as a robust measure of human performance [7]. Although extensive use of Fitts' Law has been documented in human performance literature, little work has been done to extend the paradigm to a telepresence environment. McGovern (1975) used a Fitts' Law task to demonstrate the merit of a closed loop master-slave system as compared to an open loop system [13]. Hill (1979) used a Fitts' task to demonstrate performance differences as a function of force feedback from the manipulative system [8]. Pepper (1988) was the first to use the Fitts' task in a true telepresence scenario. While previous work had employed Fitts' Law with the teleoperator in direct view of the workspace, this work used Fitts' Law to compare a variety of viewing conditions which included remote visual links between operator and workspace [16]. These studies have shown that a Fitts' Law paradigm is appropriate for analysis of perceptual-motor performance within teleoperated and true telepresence systems.

Fitts (1954) established a means of quantifying human performance in terms of information processing capacity of the neuromotor system. He developed a relationship between the speed and the accuracy of human motor performance and demonstrated that the speed of a task of requiring a particular accuracy is bounded by the capacity of the neuromuscular system control movements. Fitts argued that if manual control was limited by the information processing rate of the peripheral and central nervous system, movement times would be limited by the information processing demands of the task. This concept is apparent if we think of a task requiring great accuracy such as threading a needle. Why do we perform a threading task with infuriating sluggishness? Such a task is limited by human information processing capacity (i.e., how fast we can perceive the environment, actuate our limbs, and adjust for error). A task such as threading a needle requires

many fine adjustments and is thus limited by how quickly perceptions and adjustments can be performed (i.e., limited by human bandwidth).

To measure human information processing capacity as an indication of performance within a telepresence environment, subjects were tested on a peg insertion task. Like threading a needle, the difficulty of peg insertion is a function of tolerance, the difference between the peg diameter and the hole diameter. The tighter the fit of the peg in the hole, the more accuracy required of the operator, and thus the slower the maximum performance speed. By requiring subjects to perform a standardized peg insertion task as fast as they can, completion times could be measured and compared to task difficulty to yield information processing capacity for that task. By doing such an analysis upon subjects with and without the implementation of various virtual fixtures, variations in task completion times indicate performance changes resulting from fixture use. Thus, by using Fitts' Law analysis of a standardized peg insertion task, the effectiveness of various virtual fixtures as perceptual aids could be quantified.

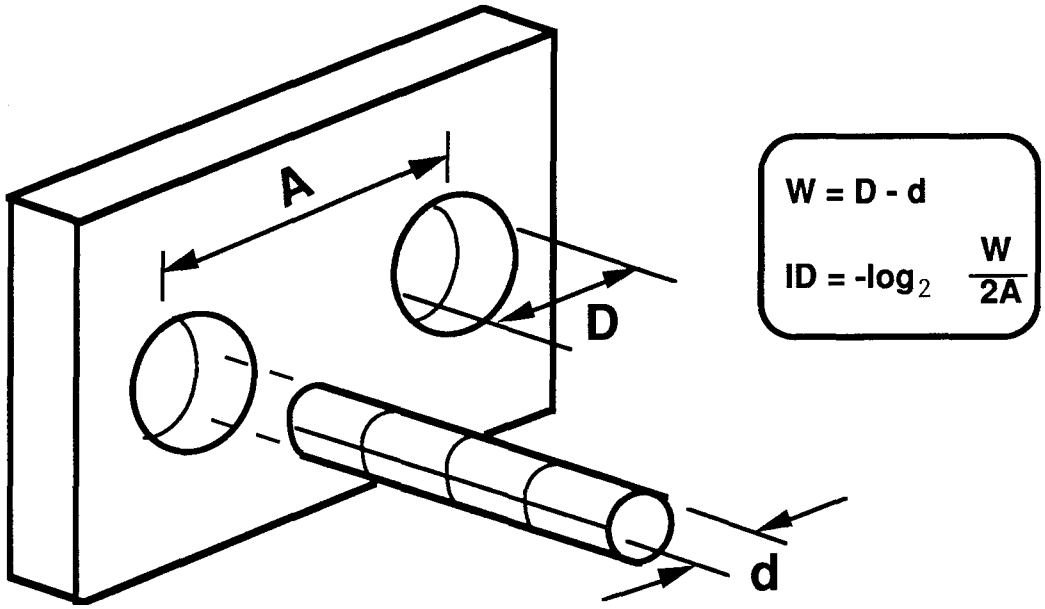

Figure 1: Measurements used to define task difficulty

Through an extensive review of human psychomotor, perceptual, and cognitive test batteries, the Naval Oceans Systems Center developed a peg insertion performance task specifically representative of teleoperator manipulative activities [16, 24]. The test battery requires subjects to move pegs of various diameters between holes of varied spacing. Movement times for peg motions are recorded and correlated with task difficulty. As defined by Fitts [7], the binary Index of Difficulty, ID, for the one dimensional peg transfer task can be computed as:

$$ID = -\log_2 \frac{W}{2A} \qquad \text{(bits/response)}$$

where A is the amplitude of the motion and W is the peg tolerance defined as the difference between the hole diameter and the peg diameter. These quantities are shown in Figure 1.

Fitts' Law [7] relates task completion time to task ID by defining the movement time, mt, as follows:

$$mt = k_1\, ID + k_2 \qquad \text{(sec)}$$

where k_1 and k_2 are characteristic constants of the individual operator and represent the slope and intercept of the Fitts' Law curve. The reciprocal of the slope of the Fitts' Law curve ($1/k_1$) has units (bits/sec) (which is identical to units of capacity for an information channel) and is thus an accepted measure of human information processing capacity [17]. Because the slope is a coarse measure and is susceptible to distortions resulting from changes in strategy between tasks of different difficulty, a more robust measure of processing capacity was also computed, called the *Binary Index of Performance*. This value, abbreviated as Ip, describes the information processing capacity required of the operator to perform a task of a particular difficulty [7]. Ip also has units (bits/sec) and is defined as follows:

$$Ip = \frac{1}{mt} \log_2 \frac{W}{2A} \qquad \text{(bits/sec)}$$

(or)

$$Ip = \frac{ID}{m\,t} \qquad \text{(bits/sec)}$$

where mt is the movement time required to complete the task. Index of Performance Ip is an accepted measure of the information processing capacity of the teleoperator [19].

Possible Performance Advantages of Virtual Fixtures

Fitts [7] demonstrated that performance in manual tasks is limited by the information processing capacity of the central and peripheral nervous systems. Virtual fixtures could enhance performance by either reducing the information processing demands of a given task or by increasing the information processing capacity of the operator. Since the fixtures are perceptual overlays and do not exist in the workspace, it would be incorrect to suggest that fixtures could in any way modify the given task. If fixtures cannot alter the task, how can they act to reduce the processing demands of the task? Although the task itself remains the same, virtual fixtures can modify how the workspace is perceived, alter how the task is conceptualized, and can thus be designed to reduce the processing demands of the task. For example, by implementing haptic fixtures as physical guides or barriers, the operator might have fewer alternative movements to consider in the *perception of the workspace* than really exist in the *actual task workspace*. Virtual guides or barriers simplify the perception of the task workspace, reduce the information processing demands on the nervous system, and thus increase operator performance. Thompson (1977) demonstrated a similar effect by showing that completion times in part mating tasks could be reduced by eliminating degrees of constraint [26]. Virtual fixtures do not eliminate constraints required by a task, but they can assist the operator in achieving some of the required constraints.

It is also hypothesized that the additional percepts offered by virtual fixtures provide localizing references to the remote workspace (i.e., interaction with the fixtures gives the operator a better sense of the physical

relationship between kinesthetic and proprioceptive output and workspace geometry). Such localization enhances the illusion of presence, provides the operator with a better understanding of the workspace, and reduces the operator's reliance on sensory feedback. This localizing effect should act to reduce the overall information processing demands of the task and ultimately enhance operator performance.

Finally, virtual fixtures could also enhance performance by providing alternative information pathways by introducing feedback from additional sensory modalities. Since the nervous system is parallel in architecture, the introduction of alternative pathways could act to increase the information processing capacity of the operator. To test these hypotheses, the following experiment measured operator performance with and without the use of simple virtual fixtures. The fixtures tested were chosen to offer insight into all three modes of operation presented above: Simplification of the perception of the task, enhanced localization to remote workspace, and increased capacity due to alternative modes of sensory feedback.

EXPERIMENTAL HARDWARE

Virtual Fixture Performance Testbed

To implement a standardized Fitts' Law performance test in a telepresence environment, the following hardware subsystems were used: Peg Insertion Task Board, MBA Exoskeletal Master/Merlin Robot Arm Slave, Monocular Vision System, and Virtual Fixture Board.

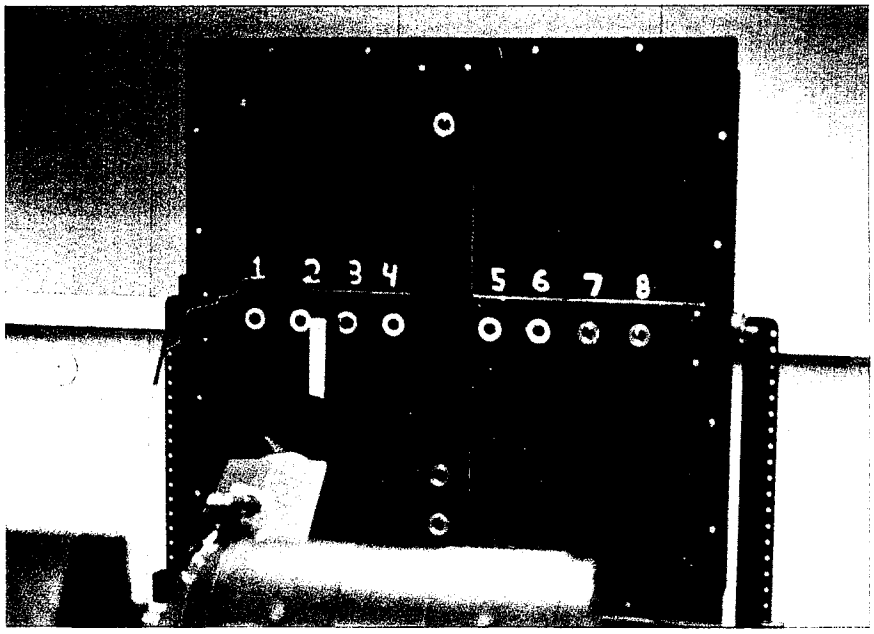

Figure 2: Photograph of the AF/Navy Teleoperator Performance Evaluation Battery Task Board used for implementing peg insertion Fitts' Law task. Also shown is the Merlin Robot Arm used as the slave in the teleoperated system.

Task Board: (AF/Navy Teleoperator Performance Evaluation Battery)

As shown in Figure 2, a specialized task board was used to implement the performance task. This task board was originally developed by the Naval Oceans Systems Center to implement a controlled peg-in-hole test battery for telemanipulation systems [16, 24]. Holes on the board are arranged to accommodate a wide range of peg sizes and movement amplitudes. This study made use of four holes (diameter 2.00 cm) spaced to allow horizontal peg movements of 4.00 cm and 16.00 cm. Three pegs (diameters 0.75 cm, 0.98 cm,

1.50 cm) were used in the task to vary the peg insertion tolerance. The bottom of each hole contains a microswitch connected to a PC via a Digital I/O controller card. This PC controls and monitors the peg insertion portion of the experiment. The computer is equipped with a real-time clock for measuring peg movement times to the nearest millisecond. The timer is started when the peg is extracted from the start hole and stopped when inserted into the target hole.

MBA Exoskeletal Master/Merlin Robot Arm Slave

As shown in Figure 3, the MBA Exoskeleton Master is a dual-arm, full upper body exoskeleton which can transduce motion in seven degrees of freedom for each arm [12]. In its current configuration, the device is used only as a sensor; no force information is reflected back to the user through the exoskeleton. Thus, peg insertions were performed based only on visual and auditory feedback from the workspace. This reduced sensory feedback environment offered a good testbed for the prowess of virtual fixtures.

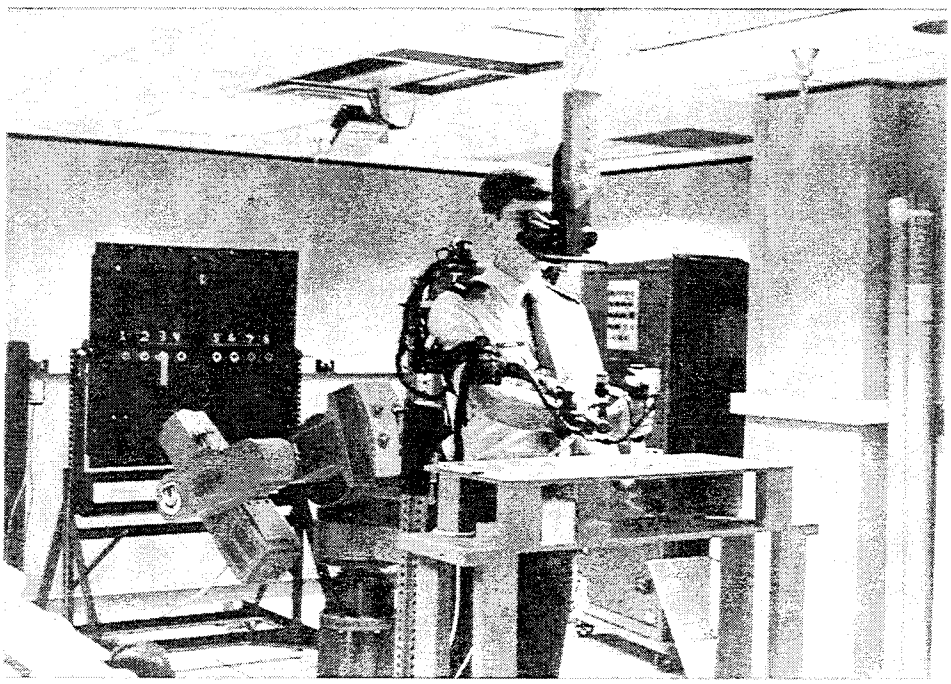

Figure 3: Photograph of subject wearing MBA kinesthetic exoskeleton used as the master in the teleoperator system.

In this experiment, the position of the subject's right hand was tracked and fed to the slave robot arm. An end-effector was constructed for the slave robot which housed the peg and allowed for easy interchange of the various diameter pegs. Because of the difficulty of the teleoperated peg insertion task without force feedback, the slave robot was programmed to maintain its end-effector orientation perpendicular to the board at all times. This arrangement simplified the task and eliminated the possibility of subjects torquing the peg in the hole. To further simplify the task, the robot was constrained to move only in a horizontal plane level with the target holes. Thus, the task only required two-dimensional positioning of the peg in the xy plane with x defined into the board, and y defined along the horizontal row of target holes as shown in Figure 4. It should be noted that although the task was constrained to planar positioningit was sufficiently difficult to require subjects to practice for two 45-minute sessions before training was complete. The task was designed to be simple in concept but difficult enough that the subjects would not approach the upper bound of the slave robot's ability to perform the task.

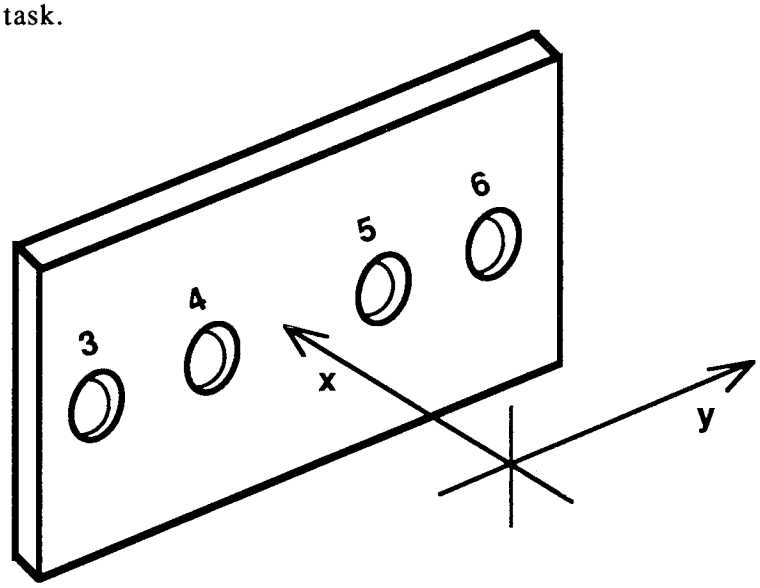

Figure 4: Schematic of Task Board with xy plane of allowable peg motion.

To protect the task board and the robot, the peg was rigidly constrained in all degrees of freedom except along the x axis pointing into the task board. Along that axis, the peg floated on a stiff spring so that strong forward impacts of the peg with the board would not jar the board or damage the robot.

Monocular Vision System

A previous study using an identical task board performed by the Naval Oceans Systems Center has shown that stereo vision feedback offers no performance advantage over monocular projections used in this peg insertion task [16, 24]. Thus, a simple monocular vision system was implemented to provide visual feedback for this experiment. The system was designed as an inexpensive means of creating the illusion of operator presence while providing visual feedback of the workspace. The system used 7X power binocular optics focused upon a distant color video monitor which displayed the output of a single camera in the workspace focused on the task board. The monitor was placed at a distance from the optics in such a way that the magnification of the video image created the illusion that the task board was within reach of the operator's hands. Robot end-effector motion was scaled to match operator hand motion so that the apparent end-effector position corresponded to the user's kinesthetic sense of arm position. Such a correlation between kinesthetic feedback and visual feedback of robot end-effector position greatly enhanced the user's sense of presence within the workspace. Testing of the system revealed best results when the angle of the camera incident on the workspace was closely matched by the angle that the magnifying optics were incident upon the distant video monitor. When these angles were not similar, conflicting perspective cues hindered the illusion of presence. Figure 5 includes a rough schematic of the vision system as part of the overall system hardware.

Virtual Fixture Board

Rather than using a force reflecting exoskeleton to model the rigid impedance surfaces which compose the virtual fixtures, it was thought that the preliminary tests of virtual fixtures should not be influenced by hardware limitations of force reflecting devices. Thus, a Fixture Board was designed which allowed real rigid surfaces to be fabricated from acrylic sheets. The MBA exoskeleton would interact with the real acrylic surfaces and reflect that information to the user. As far as the user is concerned, the haptic perception of these surfaces was coming from the exoskeleton and was just as much "virtual" information as if it was truly computer generated. The benefit of this

approach is that the reflected perception of these surfaces was perfectly modeled. The surfaces felt crisp and real, free from the bandwidth limitations of most force reflecting devices. The drawback of this approach was that more abstract fixtures were impossible to generate using this method.

The virtual fixtures were constructed out of acrylic sheets and positioned upon a wooden platform in front of the user. To make the fixtures quickly interchangeable, they were constrained and positioned on the wooden platform by locating pins. The exoskeleton was fitted with a teflon cap at the end of the hand grip which was used as the contact surface between the exoskeleton and the fixture. The fixtures were treated regularly with an oil-based lubricant so that little friction was perceivable between the teflon and the acrylic surfaces. Although frictional surfaces could make for effective virtual fixtures, the intent of this study was to look at simple surfaces modeled only as rigid impedances free from any viscous or coulombic damping.

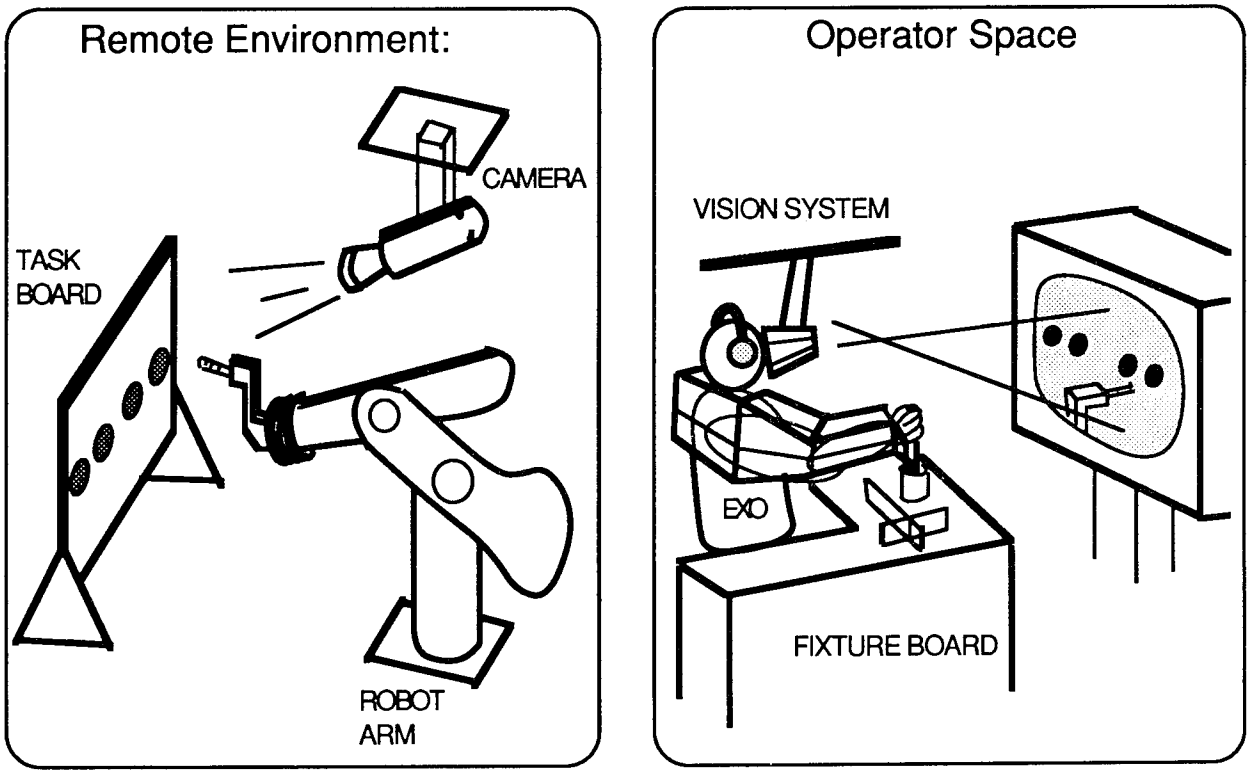

Figure 5: Complete Telepresence System developed to implement the testing of teleoperator performance in a standardized peg insertion task with and without the aid of virtual fixtures.

Although the haptic fixtures were modeled physically rather than computationally, auditory fixtures were tested that were pure computer simulations. Simple compliant surfaces were modeled in which the compression of the surface was proportional to a linear change in pitch. Tones were generated on a PC and fed to the user via stereo headphones. These trials served as a testbed for alternate modality fixtures as well as a proof of concept of purely computer-generated fixtures.

Overall Test Setup

Having described each of the major components of this test setup, it is important to clearly describe the system as a whole before getting into the details of the subject testing. As shown in Figure 5, the system is divided into two physically separate parts: the *remote environment* and the *operator space*. The remote environment contains the task board, the merlin robot arm, and a single video camera pointed at task board. The camera is positioned so that the incident perspective is similar to what a human operator would see if standing directly in front of the board and performing the peg insertions in person. The operator space contains the exoskeleton, the vision system, and the virtual fixture board. Once inside the exoskeleton and vision system, the subject is presented with a projection of the image from the camera in the remote environment. The subject is given the illusion that the task board is situated directly before him, within reaching distance of the exoskeleton. In reality, the task board is on the opposite side of the laboratory, behind the subject and completely out of view. The fixture table is placed directly in front of the subject in such a way that it cannot be seen when looking through the vision system, but feels as though it occupies the same space as the apparent image of the task board. Thus, virtual fixtures implemented on the fixture board feel as though they are overlaid on top of their perception of the remote environment.

The remote robot arm is slaved to the right hand position of the exoskeleton. Thus, when the subject moves his right hand so as to interact with the image of the task board, the end-effector on the slave arm follows. Because the subject cannot see his own hand when looking into the vision

system but does see the remote robot end-effector in the position where he feels his hand to be, a sense of presence within the remote environment is created. The subjects also wear a set of stereo headphones for use in implementing auditory perceptual overlays. Auditory surfaces and fields can be modeled on the control computer and interacted with by the user. The complete system provides a powerful testbed for projecting subjects into a remote environment and overlaying haptic and auditory information on top of the reflected percepts.

EXPERIMENT DESIGN & PROCEDURE

Experiment Design

The goal of this study was to investigate the effect that the presentation of virtual fixtures has upon performance in a standard telemanipulation task. Eight simple fixtures were developed for comparison to a no-fixture control case. Six of the test fixtures were purely haptic sensations while two fixtures introduced both haptic and auditory sensory information. It should be noted that the design of these test fixtures was *not* motivated by finding the most effective perceptual aid for this particular peg insertion task. This particular set of test fixtures was chosen to provide general insight into the design and use of virtual fixtures and to allow the evaluation of some of the *basic building blocks* from which fixtures can be made.

When designing the test fixtures, the peg insertion task was not thought of as a single motion, but rather as a combination of two phases: ballistic motion and fine positioning. The ballistic phase was defined as the time from which the peg is removed from the start hole until it makes first contact with the target hole. The fine positioning phase was defined to begin at the end of the ballistic motion and continue until the peg is properly positioned in the hole [17]. This decomposition of the peg insertion task was found to be a useful conceptual guide for fixture design. Some of the test fixtures were targeted at aiding ballistic motion, some were targeted at enhancing fine motion, and some were intended to help both. Figure 6 shows a schematic representation of each of the eight fixtures tested. These fixtures are shown overlaid on top of the task board as they are perceived by the subjects. Although these fixtures are represented graphically in this figure, they are perceived only as forces or sounds by the subjects. Although instilling visual qualities to fixtures is a viable application of perceptual overlays and an important topic for future investigation into virtual fixtures, this study was restricted only to haptic and auditory sensory modalities.

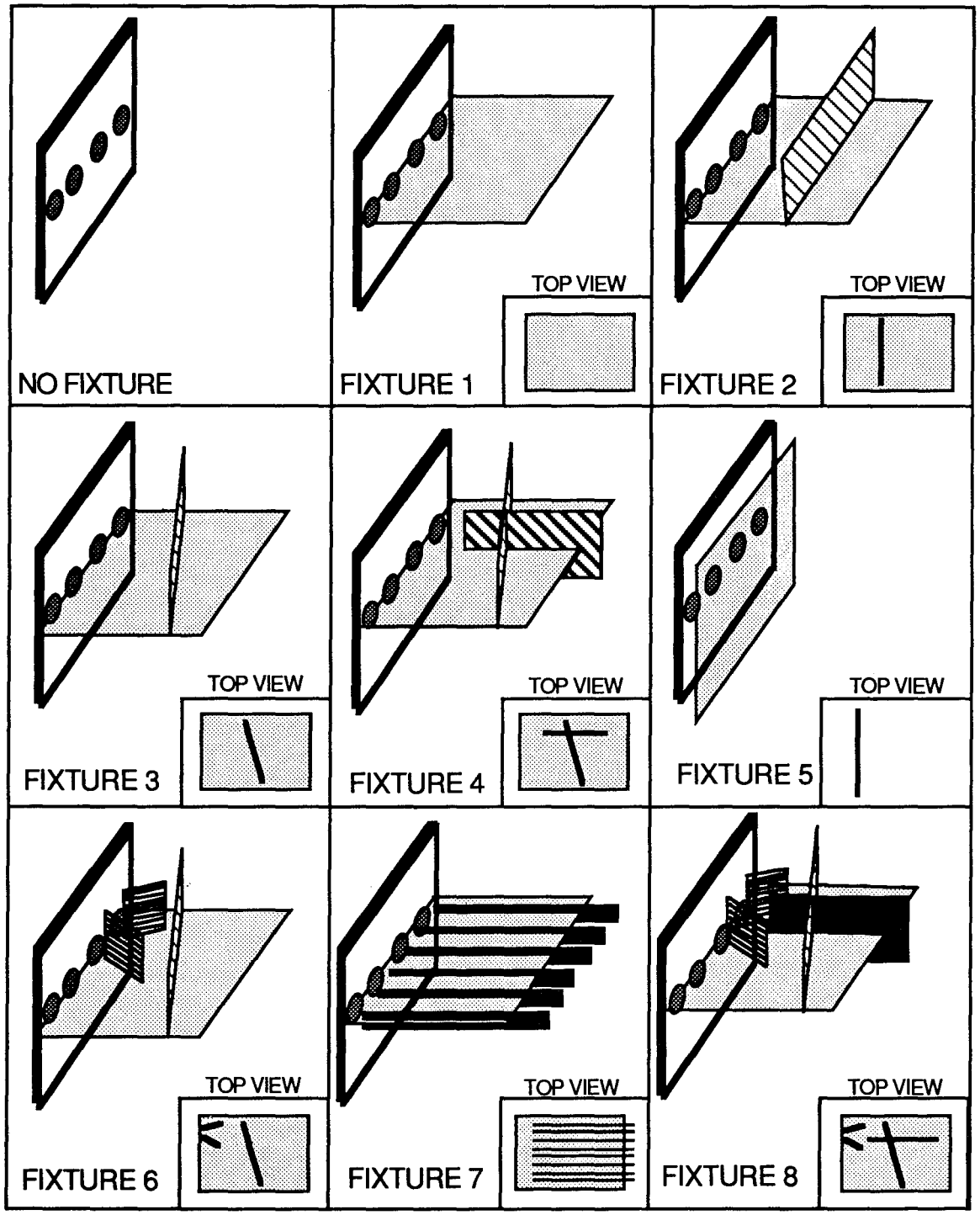

Figure 6: Virtual fixtures shown projected on top of the task board as perceived by the subjects. Also shown are top views, looking down from above the task board. The fixtures are shown graphically here, but they are perceived haptically or auditorily by subjects.

As shown in Figure 6, the eight fixtures tested are composed of simple combinations of planar surfaces. Fixture 1 is simply a rigid horizontal surface oriented like a table top in the workspace and positioned so that contact with the surface will result in vertical alignment of the operator's hand with the holes in the peg board. Fixture 2 is just like Fixture 1, but it includes a second surface which is parallel to the plane of the task board and located three inches back from the board. When using this fixture, subjects operate in the space between the vertical plane and the task board. This arrangement provides some limits upon the operator's ballistic motion. Fixture 3 is similar to Fixture 2, except the vertical plane is angled so as to converge with the task board as the target hole is approached. This arrangement acts like a funnel, confining and guiding ballistic motion towards the target hole.

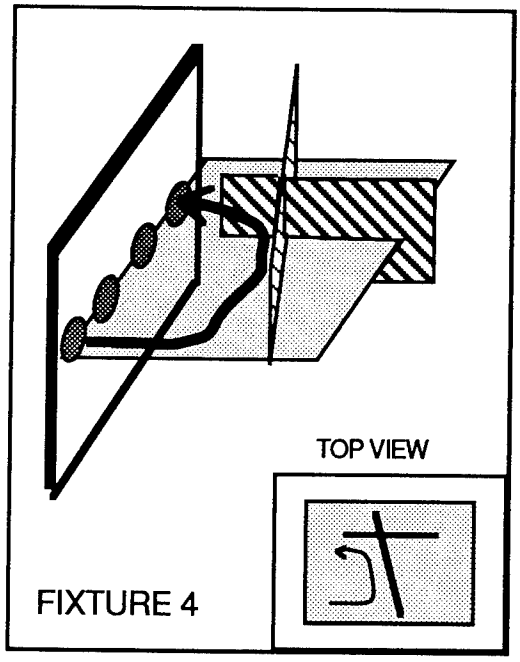

Figure 7: Sample trajectory of peg from start hole to target hole as guided by a virtual fixture. As shown, the fixture does not define the motion of the operator's hand, but rather defines the boundaries of the motion.

Fixture 4 is identical to Fixture 3, except a third plane is added directly in front of the target hole. This fixture influences the ballistic phase even further, stopping hand motion when close to the target hole. Fixture 6 is similar to

Fixture 3, except a second funnel-like fixture is added in front of the target hole. Thus, ballistic motion is guided as was done by Fixture 3, and fine motion is guided by the additional surfaces. Figure 7 shows a sample trajectory superimposed upon Fixture 4, making the fixture implementation clear. This drawing demonstrates how the use of a fixture might influence the trajectory of the peg. As shown in the figure, the rigid surfaces do not define the motion of the peg, but rather influence the operator's trajectory by confining the boundaries of peg motion.

Fixture 5 is very different from those presented thus far in both its geometry and implementation. The key is that his fixture was *not* interacted with by the subject's right hand (the hand that performed the peg insertion task), but rather was designed for interaction only with the *unused* left hand. Fixture 5 is a rigid impedance plane parallel to the task board and located approximately 0.5" in front of the board. The subject would place his left hand upon the planar surface while performing the task with the right hand. The intent of this fixture was to isolate the effect of localization on performance. It was hypothesized that all fixtures provided some localizing information to the users which enhanced their understanding of the geometry of the workspace and allowed them to better correlate their kinesthetic sense of hand position to the remote site. Because interaction with other fixtures would guide or limit the operator's motion, it was impossible to isolate performance increases due to the localizing effect alone. Thus, Fixture 5 was designed to interact only with the unused hand and therefore only affects performance by providing localizing cues.

Fixture 7 and Fixture 8 are the only fixtures which implement both haptic and auditory information. Fixture 7 is identical to Fixture 1, but also introduces a texture-like field of auditory information. The information is represented as a series of surfaces perpendicular to the task board as shown in black in Figure 6. Operator interaction with these surfaces results in the production of an audible tone. The pitch of the tone increases from left to right across the task board. Fixture 8 is identical to Fixture 6, but it introduces a single compliant surface in front of the target hole as shown in black in Figure 6. This surface is modeled as a compliant surface with a proportional

stiffness such that interaction with this surface produces a tone proportional to compression.

Experimental Protocol

A series of tests was run to evaluate subject performance using each fixture configuration. Operator performance was recorded during test periods which included 12 practice and 36 timed peg insertion trials for each fixture studied. A single trial consisted of moving a peg from a designated start hole to a designated target hole. The holes were referenced by numerals (3, 4, 5 or 6) located above each hole as shown in Figure 4. Two different peg motions were studied in these tests: a 16 cm motion from hole 3 to hole 6 and a 4 cm motion from hole 5 to hole 6. The 36 trial period was divided into three groups of 12 trials. Each of these groups required the subject to perform the insertion task using a different peg size. After the completion of each group of 12 trials, subjects were instructed to rest for approximately two minutes while a new peg size was installed in the robot end-effector.

The use of two motion amplitudes (4 cm and 16 cm) and three peg sizes (0.75 cm, 0.98 cm, 1.50 cm diameter pegs) allowed for the testing of insertion trials with six different task difficulties. Table 1 shows all combinations of peg size and motion amplitude and lists the Index of Difficulty for each task as dictated by Fitts' Law [7]. The order in which the three peg sizes were presented to each subject was randomized to ensure that mental and physical fatigue had similar effects on all task difficulties.

Table 1: *Index of Difficulties* (ID) shown for all combinations of peg size and peg motion amplitudes as predicted by Fitts' Law.

	Motion Amplitude	
Diameter	5 to 6 (4 cm)	3 to 6 (16cm)
0.75 cm	**2.68** bits/response	**4.68** bits/response
0.98 cm	**2.98** bits/response	**4.98** bits/response
1.50 cm	**4.00** bits/response	**6.00** bits/response

Subjects were instructed to begin each test period with a 3 to 6 peg insertion trial. Subjects would then perform a 5 to 6 peg insertion trial, then a 3 to 6 peg insertion trial, and cycle in that manner throughout the 36 trials. Subjects were allowed to proceed through the test period at their own pace. To automate the testing procedure and allow subjects to proceed through the test with little operator intervention, a number of simple beeps were used to guide subject activity. When a subject inserted a peg into the correct starting hole, the task board control computer would emit an audible tone to signal that the peg was properly positioned. The subject would then keep the peg in the start hole for two seconds until the control computer produced a second tone which signaled that the task could now be performed at will. The reason for this two second waiting period was to ensure that the subject maintained a steady contact with the microswitch at the base of the start hole. The subjects were *not* required to perform the insertion task as soon as the second tone was heard; this second tone simply meant "you are free to go whenever ready." Thus, the subjects could mentally prepare themselves for the particular insertion task and begin at will. When ready, the subject would remove the peg from the start hole and insert it into the target hole as fast as possible. Upon insertion into the target hole, the control computer would emit a tone to signal that the trial had been successfully completed. The subject was then free to proceed to the next insertion trial at will. At the end of each trial the control computer recorded the movement time along with the peg size and motion amplitude. After the completion of each group of 12 trials, the control computer would emit a long-duration tone which signaled the subject to rest for two minutes while the operator exchanged peg sizes. Post testing interviews revealed that all subjects were comfortable with the use of audible tones to automate the testing procedure.

Subjects were tested over 9 experimental sessions, each lasting 45 to 60 minutes. To minimize the effects of fatigue and boredom, no subject completed more than one experimental session during a single day of testing. Each of the first two experimental sessions included two test periods of 36 trials. The first period of each session was performed with no fixture and the second was performed with Fixture 1. These initial 144 trials were treated only as practice during which the subjects familiarized themselves with the use of the exoskeleton, merlin robot arm, vision system, and fixture table. It was found

that by the end of the second practice session, all subjects had sufficiently learned the task that variability in movement times for trials of the same difficulty had fallen below 20% for every subject, with a mean variability of 14% for all subjects. Once learning had stabilized, subjects were sequentially tested using each of the test fixtures. One or two new fixtures were tested during each daily session in addition to a baseline fixture which was tested during every session. Fixture 1 was the baseline fixture and was used to track performance increases resulting from day-to-day learning so that any such effects could be compensated. Table 2 lists all of the daily sessions along with the fixtures tested during that session.

Table 2: *Testing Schedule:* All seven tests shown along with corresponding daily sessions and fixtures tested on that day.

TEST	SESSION	FIXTURES STUDIED
Practice	day 1	No Fixture / Fixture 1
Practice	day 2	No Fixture / Fixture 1
Test I	day 3	No Fixture / Fixture 1
Test II	day 4	Fixture 1 / Fixture 2 / Fixture 3
Test III	day 5	Fixture 1 / Fixture 4
Test IV	day 6	Fixture 0 / Fixture 5
Test V	day 7	Fixture 1 / Fixture 6
Test VI	day 8	Fixture 1 / Fixture 8
Test VII	day 9	Fixture 1 / Fixture 7

RESULTS

The following section presents all results of fixture performance comparisons in tabular form. The basic quantities presented are the recorded movement times and the coefficients of variation of movement times for trials of the same difficulty. The coefficient of variation is a measure of subject consistency at a particular task and is an indication of the repeatability of the results. Also computed is the slope of a linear regression line relating movement time to index of difficulty. The inverse of the slope has units (bits/sec) and is a measure of the operator information processing capacity. Because the slope is susceptible to distortions resulting from changes in strategy between tasks of different difficulty, a more robust measure of processing capacity was also computed called the *Binary Index of Performance*. This value, abbreviated as Ip, describes the information processing capacity required of the operator to perform a task [7].

Tables 3 through 5 list the mean movement time results for each fixture tested. Tables 6 through 8 list the computed Index of Performance (Ip) for each fixture tested. Table 9 lists the coefficients of variation, slopes, and the inverse of the slopes for each fixture tested. Figure 8 graphically compares the performance, showing the mean movement time versus index of difficulty curves for all test fixtures.

TABLE 3: *Mean Movement Times* for each Index of Difficulty are shown for 8 subjects using no fixture as well as using Fixtures 1, 2, 3, 4 and 6. Also computed is the mean movement time across all trials (across task difficulty).

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
No Fixture	1123ms	1280ms	1353ms	1946ms	1866ms	2162ms	1622ms
Fixture 1	957ms	977ms	1118ms	1595ms	1656ms	1758ms	1344ms
Fixture 2	842ms	883ms	1030ms	1435ms	1527ms	1631ms	1225ms
Fixture 3	682ms	704ms	795ms	1293ms	1350ms	1469ms	1049ms
Fixture 4	692ms	713ms	815ms	1376ms	1471ms	1543ms	1102ms
Fixture 6	667ms	722ms	835ms	1301ms	1385ms	1495ms	1068ms

TABLE 4: *Mean Movement times* for each Index of Difficulty are shown for 6 subjects using no fixture as well as using the localizing Fixture 5 with the unused hand. Also computed is the mean movement time across all trials (across task difficulty).

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
No Fixture	833ms	927ms	991ms	1617ms	1600ms	1666ms	1272ms
Fixture 5	656ms	662ms	807ms	1448ms	1396ms	1497ms	1078ms

TABLE 5: *Mean Movement Times* for each Index of Difficulty are shown for 6 subjects using no fixture, using purely haptic Fixtures 1 and 6, as well as using auditory/haptic Fixtures 7 and 8. Also shown is the mean movement time across all trials. It should be noted that Fixtures 1 and 7 are identical except for the addition of auditory information in 7. The same is true for Fixture 6 and Fixture 8.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
No Fixture	1073ms	1177ms	1259ms	1845ms	1832ms	2058ms	1541ms
Fixture 1	840ms	910ms	969ms	1539ms	1569ms	1674ms	1250ms
Fixture 7	687ms	727ms	718ms	1310ms	1325ms	1369ms	1023ms
Fixture 6	641ms	691ms	811ms	1266ms	1361ms	1461ms	1039ms
Fixture 8	614ms	610ms	701ms	1136ms	1154ms	1270ms	915ms

TABLE 6: *Index of Performance,* Ip = (ID / mean movement time), is computed and shown for 8 subjects using no fixture as well as using Fixtures 1, 2, 3, 4 and 6. Ip has units (bits/sec) and is an accepted measure of human information processing capacity.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean Ip
No Fixture	2.34	2.33	2.96	2.40	2.67	2.77	2.58
Fixture 1	2.80	2.99	3.58	2.93	3.01	3.41	3.12
Fixture 2	3.18	3.37	3.88	3.26	3.26	3.68	3.44
Fixture 3	3.93	4.23	5.03	3.62	3.69	4.08	4.10
Fixture 4	3.87	4.18	4.91	3.40	3.39	3.89	3.94
Fixture 6	4.02	4.13	4.79	3.60	3.60	4.01	4.02

TABLE 7: *Index of Performance*, Ip = (ID / mean movement time), is computed and shown for 6 subjects using no fixture as well as using the localizing Fixture 5 with the unused hand. Ip has units (bits/sec) and is an accepted measure of human information processing capacity.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean Ip
No Fixture	3.22	3.21	4.03	2.89	3.11	3.60	3.60
Fixture 5	4.09	4.50	4.96	3.23	3.58	4.01	4.01

TABLE 8: *Index of Performance*, Ip = (ID / mean movement time) , is computed and shown for 6 subjects using no fixture, using purely haptic Fixtures 1 and 6, as well as using auditory/haptic Fixtures 7 and 8. Ip has units (bits/sec) and is an accepted measure of human information processing capacity. It should be noted that Fixtures 1 and 7 are identical except for the addition of auditory information in 7. The same is true for Fixture 6 and Fixture 8.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean Ip
No Fixture	2.50	2.67	3.18	2.54	2.72	2.92	2.76
Fixture 1	3.19	3.27	4.12	3.04	3.17	3.58	3.40
Fixture 7	3.90	4.01	5.57	3.57	3.76	4.38	4.20
Fixture 6	4.18	4.31	4.93	3.70	3.66	4.11	4.15
Fixture 8	4.36	4.88	5.71	4.12	4.32	4.72	4.69

Table 9: *Mean Coefficient of Variation* for all subjects performing tasks of the same difficulty with each fixture is shown. Also shown is the slope and standard error of a linear regression analysis of movement time against index of difficulty. The reciprocal of the slope is also shown and has units (bits/sec). This value is an accepted measure of information processing capacity.

FIXTURE	MEAN C.O.V.	SLOPE [ms/bit]	Std Err of Coef	1/SLOPE [bits / sec]
No Fixture	13.7% ±2.5	317	43	3.15
Fixture 1	11.9% ±2.0	276	39	3.62
Fixture 2	12.8% ±3.2	267	37	3.75
Fixture 3	11.1% ±2.7	271	47	3.69
Fixture 4	8.6% ±1.9	300	56	3.33
Fixture 5	13.0% ±1.3	302	62	3.31
Fixture 6	9.6% ±2.8	280	44	3.57
Fixture 7	11.2% ±1.9	244	61	4.10
Fixture 8	9.2% ±1.5	228	40	4.39

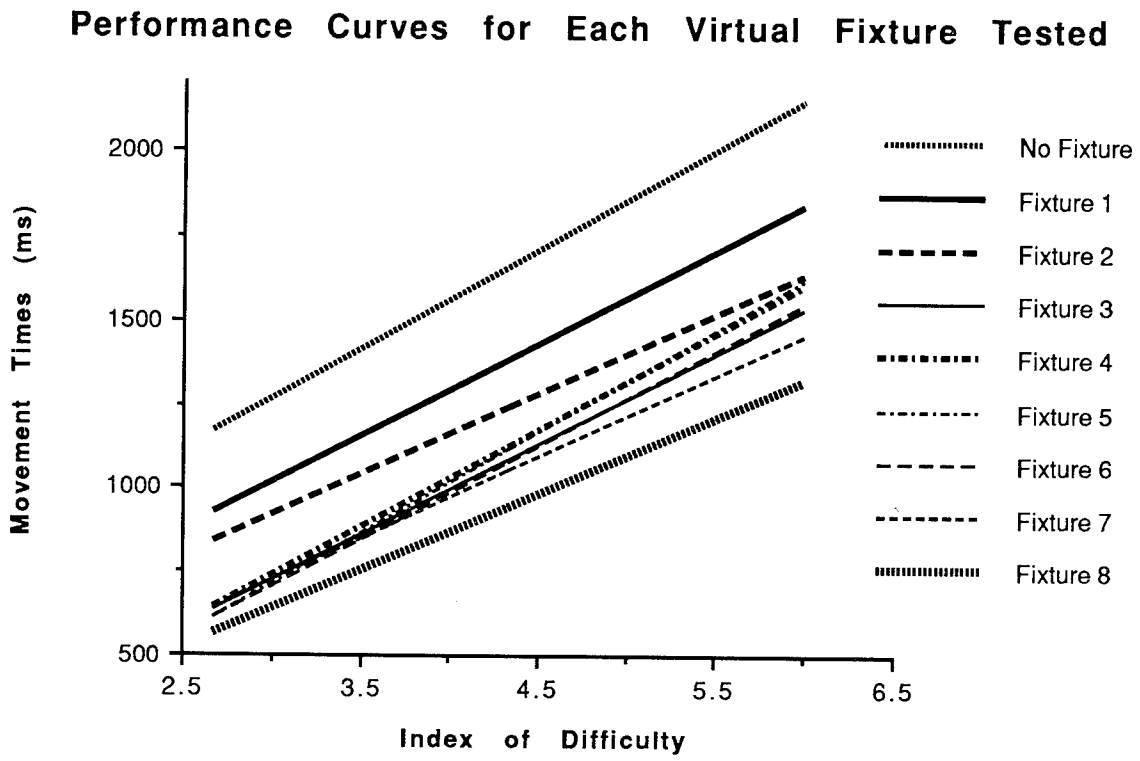

Figure 8: Performance using each fixture shown for comparison as best line fit to Fitts' Law relation between mt and ID

In order to quantify performance increase due to fixture use in a meaningful way that is resistant to variations across task difficulty, percentage changes in movement times and Index of Performance were computed for each fixture with respect to the no-fixture case. The percentage decrease in movement times is a unitless measure of the effectiveness of a fixture to speed operator performance in a task. The percentage increase in Index of Performance is a unitless measure of the increase in the information processing capacity of the operator or the decrease in processing requirements of the task resulting from fixture use. Tables 10 and 11 list the percentage decrease in movement times corresponding to the use of each fixture. Tables 12 and 13 list the percentage increase in processing capacity Ip associated with the use of each fixture.

TABLE 10: *Percent Decrease in Movement Time* for each fixture with respect to the no-fixture case. Values are computed for each index of difficulty. Also shown is the mean percentage decrease in movement time for each fixture. This mean value represents the effectiveness of a fixture to enhance operator performance.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
Fixture 1	15.96%	26.85%	19.02%	19.82%	11.93%	20.61%	19.03% ±4.9
Fixture 2	28.60%	36.71%	27.11%	30.23%	19.98%	28.00%	28.44% ±5.4
Fixture 3	48.86%	58.06%	51.96%	40.32%	32.09%	38.17%	44.91% ±9.1
Fixture 4	47.49%	56.90%	49.63%	34.32%	23.67%	33.41%	40.90% ±11.9
Fixture 5	23.77%	33.35%	20.47%	11.03%	13.62%	10.69%	18.82% ±7.9
Fixture 6	50.95%	55.74%	47.35%	39.73%	29.59%	36.48%	43.31% ±9.2
Fixture 7	43.86%	47.27%	54.73%	33.91%	32.12%	40.21%	42.02% ±8.4
Fixture 8	54.42%	63.46%	56.94%	47.57%	45.41%	47.36%	52.52% ±6.5

TABLE 11: *Percentage Decreases in Movement Times* when using Fixtures 7 and 8 as compared to Fixtures 1 and 6 respectively. Since Fixtures 7 and 8 are identical to 1 and 6 in all ways except for the addition of auditory information, the percentage decrease in movement times reflects the performance advantage associated with overlaying auditory information.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
Fixture 7	20.04%	22.36%	29.76%	16.08%	16.86%	20.05%	20.89% ±4.9
Fixture 8	4.30%	12.45%	14.55%	10.82%	16.46%	13.99%	12.10% ±4.2

TABLE 12: *Percent Increase in Processing Capacity* Ip for each fixture with respect to the no-fixture case. Values are computed for each index of difficulty. Also computed is the mean percentage increase in processing capacity associated with each fixture.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
Fixture 1	19.66%	28.33%	20.95%	22.08%	12.73%	23.10%	21.14% ± 5.0
Fixture 2	35.90%	44.64%	31.08%	35.83%	22.10%	32.85%	33.73% ± 7.4
Fixture 3	67.95%	81.55%	69.93%	50.83%	38.20%	47.29%	59.29% 15.3
Fixture 4	65.38%	79.40%	65.88%	41.67%	26.97%	40.43%	53.29% ±18.9
Fixture 5	27.02%	40.19%	23.08%	11.76%	15.11%	11.39%	20.31% ±10.8
Fixture 6	71.79%	77.25%	61.82%	50.00%	34.83%	44.77%	56.74% ±15.3
Fixture 7	56.00%	50.19%	75.16%	40.55%	38.24%	50.00%	51.69% ±13.2
Fixture 8	74.40%	82.77%	79.56%	62.20%	58.82%	61.64%	69.90% ± 9.5

TABLE 13: *Percentage Increases in Processing Capacity* Ip when using Fixtures 7 and 8 as compared to Fixtures 1 and 6 respectively. Since Fixtures 7 and 8 are identical to 1 and 6 in all ways except for the addition of auditory information, the percentage increase in Ip reflects the performance advantage associated with overlaying auditory information.

	INDEX OF DIFFICULTY						
FIXTURE	2.68	2.98	4.00	4.68	4.98	6.00	mean
Fixture 7	22.26%	22.63%	35.19%	17.43%	18.61%	22.35%	23.08% ±6.3
Fixture 8	4.31%	13.23%	15.82%	11.35%	18.03%	14.84%	12.93% ±4.7

DISCUSSION

Analysis of Each Test Fixture

The following section sequentially addresses the change in performance associated with each fixture and discusses the implications. The objective of this analysis is to gain general insight into the fundamental properties of virtual fixtures in order to facilitate the design and implementation of an interactive perceptual workstation.

Before comparing the performance results for task completion with each fixture configuration, the issue of repeatability and reliability of the results should be addressed. As shown in Table 9, the coefficients of variation for task completion is under 14% for all fixture configurations, with a mean variability of 10%. This means that for any given task of a particular difficulty performed by any given subject, the variation in performance for all such trials was on average 10%. Such consistency for human performance is surprisingly good and suggests that the results of these tests are highly reliable.

Virtual Fixture 1

As shown in Figure 6, virtual Fixture 1 is a rigid impedance plane oriented perpendicularly to the plane of the task board. When interacting with this fixture, the subject's hand motion is restrained to move only in the plane of the peg holes. Thus, this fixture reduces the Cartesian degrees of freedom on hand motion from three to two. An interesting point about this fixture is that the end-effector of the slave robot is restricted by software to planar two degree of freedom motion regardless of the operator's commands. Thus, the degree of freedom which is eliminated by the use of Fixture 1 has no effect on the position of the slave robot arm. Since this degree of freedom plays no part in performing the task, it would seem that Fixture 1 would have little effect on the performance of the operator.

As shown in Tables 3 and 10, the mean movement times for peg insertions performed with the aid of virtual Fixture 1 was 19% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in

Tables 6 and 12, the human information processing capacity when using virtual Fixture 1 was 21% greater than with no fixture at all. This comparison suggests that a virtual fixture can enhance performance by simplifying the perception of the task even though the task itself is unchanged. In both cases, the peg insertion task was a 2 degree of freedom operation. Without the fixture, the subjects were free to move in all three Cartesian directions even though they were well aware that the slave robot's position was locked in the y direction. With the fixture, the subjects were guided to move only in the plane. This implies that even after the 144 trials of practice, the subjects were unable to completely ignore the irrelevant degree of freedom and were wasting processing capacity on it. This result suggests, first, that use of the single rigid impedance plane as a virtual fixture was effective in significantly increasing operator performance. Second, this result suggests that when developing a presence system which interfaces a human limb to a robot arm with fewer degrees of freedom, the unused degrees of freedom may degrade performance and thus should be restrained whenever possible.

Think back to the example given earlier which proposed the use of a virtual fixture similar to Fixture 1 to enhance performance in a telepresence system for surgery. A single rigid impedance plane was described which could be located at some depth below the tissue of a patient such that interaction of the surgeon's scalpel with this rigid surface could assure that the incision only reached a particular depth, thus protecting vital organs. The results of testing with Fixture 1 suggest that not only would such a fixture limit motion to the plane and thus maintain a constant incision depth, it would also enhance operator ability to perform in free plane and increase information processing capacity. Thus, not only would the surgeon be safe from encountering vital organs located beneath the protective surface, the surgeon would have enhanced dexterity above the surface.

Virtual Fixture 2

As shown in Figure 6, virtual Fixture 2 is the same as Fixture 1 except a second rigid planar impedance surface is added parallel to the surface of the task board. Like Fixture 1, Fixture 2 restricts operator hand motion to the horizontal plane. The added surface also restricts how far back from the board the operator can draw the peg. As shown in Tables 3 and 10, the mean movement times for peg insertions performed with the aid of virtual Fixture 2 were 28% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 6 and 12, the human information processing capacity when using virtual Fixture 2 was 34% greater than with no fixture at all. This comparison clearly shows that the use of Fixture 2 significantly enhanced performance over the no-fixture case and that use of the additional surface in Fixture 2 as compared to Fixture 1 made a significant improvement. The question thus remains, why should the additional surface in Fixture 2 increase performance? It is believed that the additional surface serves a number of purposes by restricting how far back the peg can be drawn from the board: First, this surface guides operator ballistic motion, preventing unnecessarily wide trajectories. This should reduce the information processing required of the task because the distance from the task board is no longer a parameter the operator needs to be constantly concerned with. Secondly, this surface acts as a kinesthetic/proprioceptive localizing agent, giving the user a better sense of hand position in the remote workspace by providing a haptic indication of proximity from the task board. Thirdly, by providing depth information haptically, the fixture reduces the demand on the visual system to gage depth and frees up that modality for other uses, like tracking the target hole.

Virtual Fixture 3

As shown in Figure 6, virtual Fixture 3 is the same as Fixture 2 except the second rigid planar impedance surface is not parallel to the surface of the task board, but rather is diagonal. Like Fixture 1, Fixture 3 restricts operator hand motion to the plane. Like Fixture 2, the additional surface restricts how far back from the board the operator can draw the peg. The unique thing

about Fixture 3 is that it does not uniformly restrict how far back the peg can be drawn, but rather converges hand motion toward the board as the target hole is approached. Although this fixture is composed of 2 intersecting planes, it can be thought of as a cone projected into the two dimensional workspace which funnels ballistic motion towards the target hole. As shown in Tables 3 and 10, the mean movement times for peg insertions performed with the aid of virtual Fixture 3 were 45% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 6 and 12, the human information processing capacity when using virtual Fixture 3 was 59% greater than with no fixture at all. Like Fixture 2, this fixture provides haptic depth cues and kinesthetic/proprioceptive localization to the remote workspace. The primary advantage of this fixture is that it guides ballistic motion more efficiently, funnelling the gross motion towards the target hole. It is believed that this perceptual aid in target convergence reduces the demand upon kinesthetic and visual feedback and thus reduces the information processing required for the task.

Virtual Fixture 4

As shown in Figure 6, virtual Fixture 4 is the same as Fixture 3 except for the addition of a third rigid impedance surface which crosses the diagonal surface. This additional surface was placed such that the operator would contact this surface when the peg was directly in front of the target hole. Whereas Fixture 3 aided ballistic motion by converging hand position towards the target hole, Fixture 4 was intended to provide further trajectory shaping by halting hand motion when the peg was aligned with the hole. As shown in Tables 3 and 10, the mean movement times for peg insertions performed with the aid of virtual Fixture 4 were 41% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 6 and 12, the human information processing capacity when using virtual Fixture 4 was 53% greater than with no fixture at all. The results for Fixture 4 are not significantly different from those for the Fixture 3 case, showing that the addition of the third surface did not enhance performance in these trials. It is thus concluded that the additional surface added no important information for task completion. An interesting side note is that in a time delay study currently being completed, Fixture 4 was found to provide significant

improvement over Fixture 3 when communication delays were introduced into the system. This makes sense because additional localizing references become more important when time delays distort the relation between kinesthetic sense of position and visual feedback of position. These results will be presented formally in a companion paper addressing time delay issues.

Virtual Fixture 5

As shown in Figure 6, virtual Fixture 5 is composed of a single rigid impedance plane which is parallel to the task board surface and is located approximately 0.5" in front of the board. Whereas all fixtures thus far described were designed for interaction with the operator's right hand (the hand that manipulates the peg), Fixture 5 is designed for interaction only with the operator's unused hand. Subjects place the palm of their left hand upon the surface while they perform the task with their right hand. The purpose of testing this fixture was to isolate the effect of localization upon performance because this fixture can only influence performance through pure localization. The idea for this fixture was developed while observing operators perform the peg insertion task in person (not telepresent). All subjects rested their unused left hand upon the task board while performing the task with their right hand. This suggested that the operators gathered useful localizing information from the unused hand. As shown in Tables 3 and 10, the mean movement times for peg insertions performed with the aid of virtual Fixture 5 were 19% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 6 and 12, the human information processing capacity when using virtual Fixture 5 was 20% greater than with no fixture at all. These results suggest that kinesthetic/proprioceptive localization to the remote site plays an important part in the effectiveness of virtual fixtures to enhance performance. These results further suggest the importance of telepresence systems which allow for bilateral (dual arm) interaction with the workspace even if for tasks which only require one hand.

Virtual Fixture 6

As shown in Figure 6, virtual Fixture 6 is identical to Fixture 3 with the addition of two angled surfaces which guide hand motion directly into the target hole. While Fixture 3 guides ballistic motion by converging near the target hole, Fixture 6 also guides fine motion by converging hand position directly into the center of the target hole. Although this fixture is composed of 4 intersecting planes, it can be thought of as two cones projected into the two dimensional workspace. One cone funnels ballistic motion across the length of the board; the other cone funnels fine motion into the target hole. As shown in Tables 3 and 10, the mean movement times for peg insertions performed with the aid of virtual Fixture 6 were 43% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 6 and 12, the human information processing capacity when using virtual Fixture 6 was 57% greater than with no fixture at all. The results for Fixture 6 are not statistically different from those for the Fixture 3 case, thus showing that the addition of the fine positioning surfaces did not enhance performance in these trials. This result suggests that ballistic motion accounted for the most significant part of movement times. An interesting side note is that in a time delay study currently being completed, Fixture 6 was found to provide significant improvement over Fixture 3 when communication delays were introduced into the system. This makes sense because fine position becomes more difficult when time delays are present. These results will be presented formally in a companion paper addressing time delay issues.

Virtual Fixture 7

As shown in Figure 6, virtual Fixture 7 is identical to Fixture 1 with the addition of field-like auditory feedback. The sonic information is modeled as a series of parallel planes such that crossing of each plane results in a tone of a given frequency. As planes are crossed from left to right, the frequency associated with each plane increases. Both the density of auditory pulses and the pitch of each pulse are useful cues. The result is a texture-like sonic field which provides rich position, velocity, and acceleration feedback to the operator. As shown in Tables 5, 10 and 11, the mean movement times for peg insertions performed with the aid of virtual Fixture 7 were 20% faster than the

Fixture 1 case and 42% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 8, 12 and 13, the human information processing capacity when using virtual Fixture 7 was 23% greater than the Fixture 1 case and 52% greater than with no fixture at all. The over 20% improvement in performance when using Fixture 7 over Fixture 1 (which differ only by the addition of auditory information in 7) strongly suggests that the use of multiple sensory modalities increases information processing capacity and is thus a powerful tool in fixture design. It further suggests that overlaying an auditory gradient field on top of the workspace to provide position, velocity, and acceleration cues is a simple means of enhancing operator performance. Post testing subject interviews revealed that most subjects were unaware that their performance increased with the additional auditory information, but all reported having a better sense of the shape of their peg insertion trajectories.

Virtual Fixture 8

As shown in Figure 6, Fixture 8 is identical to Fixture 6 with the addition of an auditory compliant surface modeled such that compression of the surface corresponds to increasing pitch of the auditory feedback. The surface is positioned such that first contact occurs just before the peg should be inserted into the target hole. This auditory surface provides a well positioned localizing reference to act as a warning signal to indicate that the peg has traveled far enough and now should be inserted. As shown in Tables 5, 10 and 11, the mean movement times for peg insertions performed with the aid of virtual Fixture 8 were 12% faster than the Fixture 6 case and 53% faster than with the no-fixture case. Comparing Indexes of Performance (Ip) as shown in Tables 8, 12 and 13, the human information processing capacity when using virtual Fixture 8 was 13% greater than the Fixture 6 case and 70% greater than with no-fixture at all. The over 12% improvement in performance when using Fixture 8 over Fixture 6 (which differ only by the addition of auditory information in 8) suggests that the use of the additional modality was useful in increasing information processing capacity. It should also be noted that of all the fixtures tested, the use of Fixture 8 resulted in the greatest improvement in movement times and Index of Performance over the no-fixture case. This suggests that the use of multiple modalities in fixture design is a powerful

perceptual aid and should be expanded to visual and tactile information as well. Post testing interviews revealed that the use of the auditory fixtures caused subjects to alter their conceptualization of the task such that a successful trial no longer just looked and felt a certain way, but also sounded a certain way.

We can further compare the advantage of using multiple modalities in fixture design by analyzing the slopes of the Fitts' Law curve relating movement times to Index of Difficulty for each fixture. The inverse of the slope of the Fitts' Law curve, computed by linear regression and listed in Table 9, has units (bits/sec) and is an accepted measure of overall information processing capacity of the operator. This information is also represented in graphical form in Figure 8. Comparing each fixture tested, the two fixtures whose use resulted in the greatest overall increase in information processing capacity were Fixtures 7 and 8, the only two fixtures to introduce auditory information. This analysis further supports the idea that using virtual fixtures to introduce abstract sensory information from multiple modalities is a viable method of enhancing operator performance.

CONCLUSIONS

The results of this study confirm that overlaying abstract sensory information in the form of *virtual fixtures* on top of the sensory feedback from a remote environment can greatly enhance performance in telemanipulation tasks. Virtual fixtures composed of simple combinations of rigid impedance surfaces and abstract auditory information increased operator performance by up to 70% in a standard peg insertion task. It should be noted that a peg insertion task was chosen for this study because it offered an effective means of quantifying operator performance and not because it was thought to be a particularly good application for virtual fixtures. Although virtual fixtures proved to be an effective means of improving peg insertion performance, it is likely that the fixtures would have had a much greater impact upon the performance of a more challenging telemanipulation task.

Because effective virtual fixtures were developed from very basic elements like rigid impedance surfaces and simple gradient fields, the development of an interactive *perceptual workstation* that allows an operator to build virtual fixtures from basic building blocks seems like a feasible endeavor. Such an interactive workstation could allow a teleoperator to develop powerful virtual fixtures upon first encounter with an unfamiliar task in an unstructured environment. Such a workstation might also allow an operator to quickly modify a fixture as task conditions change.

Analysis of some basic perceptual elements tested in this study suggests that virtual fixtures enhance operator performance in the following ways:

1. Virtual fixtures simplify the operator's interaction with the remote workspace by restricting unnecessary kinematic freedoms and preventing unwanted actions from occurring. This simplification limits the alternatives the operator has to consider and reduces the information that needs to be processed. This simplification also allows the operator to relax criteria for success and failure by eliminating some modes of failure and by providing assistance in achieving some aspects of a successful task completion.

2. Virtual fixtures alter the operator's conceptualization of the remote task by introducing abstract sensory information into the workspace. Without the aid of any virtual fixturing, the remote peg insertion task was primarily a visual operation. Thus, the operator was likely to conceptualize the peg insertion task as a manual procedure that "looks a certain way." With virtual fixtures, additional haptic and auditory information is provided to the operator. This additional sensory information allows the operator to conceptualize the peg insertion task as not just "looking a certain way" but also as "feeling a certain way" and "sounding a certain way."

3. Virtual fixtures were shown to provide a localizing reference to the remote worksite by introducing haptic and auditory cues that can be coupled to the operator's kinesthetic sense of workspace geometry. This was demonstrated dramatically by test Fixture 5 which allowed a 20% performance improvement by providing haptic localizing information to the operator's unused hand.

4. Virtual fixtures can displace the burden from taxed sensory modalities by providing information through alternative sensory pathways. Without the aid of virtual fixtures, the peg insertion task primarily taxed the visual modality. With the fixtures, haptic and auditory sensations could also be relied upon. Had this task required additional use of the visual modality for scanning the scene or monitoring some other aspect of the task, the beneficial effect of displacing the burden from the visual modality would likely have been even more pronounced.

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Addendum:

Virtual Fixtures Project (augmented reality research) - Wright Patterson AFB, 1992

Footnote: the Virtual Fixtures project was funded by the Air Force Office of Scientific Research (AFOSR) and is therefore entered into the public domain. The research was conducted at Stanford, Air Force Research Laboratory (Armstrong Lab), and NASA Ames Research Center. The objective of the Virtual Fixtures platform was to research whether it was possible to incorporate interactive virtual objects (called "virtual fixtures") into a user's perception of real workspaces. This concept later became commonly referred to as augmented reality (AR) or mixed reality (MR).